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Magnetospheric Structure and Non-Thermal Emission of AXPs and SGRs

M. Lyutikov[1,2,3], C. Thompson[4], S.R. Kulkarni[5]

Abstract. In the framework of the magnetar model for the Soft Gamma Repeaters and Anomalous X-ray Pulsars, we consider the structure of neutron star magnetospheres threaded by large-scale electrical currents. We construct self-similar, force-free equilibria under the assumption of axisymmetry and a power law dependence of magnetic field on radius, $\mathbf{B} \propto r^{-(2+p)}$. A large-scale twist of the field lines softens the radial dependence to $p < 1$, thereby accelerating the spindown torque with respect to a vacuum dipole. A magnetosphere with a strong twist ($B_\phi/B_\theta = O(1)$ at the equator) has an optical depth ~ 1 to resonant cyclotron scattering, independent of frequency (radius), surface magnetic field strength, or the charge/mass ratio of the scattering charge. We investigate the effects of the resonant Compton scattering by the charge carriers (both electrons and ions) on the emergent X-ray spectra and pulse profiles.

1. Nature of the AXPs and SGRs

The Anomalous X-ray Pulsars and Soft Gamma Repeaters are neutron stars which share similar spin periods, $P = 5 - -12$ s, characteristic ages, $P/\dot{P} = 3\times10^3 - 4\times10^5$ yr, and X-ray luminosities, $L_X = 3\times10^{34} - 10^{36}$ erg s^{-1}, well in excess of the spin-down luminosities (Thompson et al. 2001). They are almost certainly young and isolated: no evidence for a binary stellar companion has yet been detected in any of these sources, and a few are convincingly associated with young supernova remnants. The overlap between the SGR and AXP sources in a three-dimensional parameter space (P, $\dot{P}$ and L_X), and the observed variabil-

[1]Department of Physics, McGill University, Montréal, QC

[2]Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139

[3]CITA National Fellow

[4]Canadian Institute for Theoretical Astrophysics, 60 St. George St., Toronto, ON M5S 3H8

[5]California Institute of Technology, 105-24, Pasadena, CA 91125

ity in their X-ray output, provides circumstantial evidence that they share a common energy source: the decay of a very strong ($\gtrsim 10^{15}$ G) magnetic field.

The persistent emission of the SGRs and AXPs has both a thermal and a non-thermal component. In the case of the SGRs, this emission becomes brighter after periods of bursting activity and involves a comparable release of energy to the outbursts (averaged over time).

2. Twisted Neutron Star Magnetospheres

The magnetic fields of magnetars are most likely generated by a hydromagnetic dynamo as the star is born, and may be associated with rapid initial rotation (Duncan & Thompson 1992). A strong twist in a $\sim 10^{15}$ G magnetic field will relax at intervals as the field is transported through the deep interior of the neutron star. Even if the electrical current were initially confined to interior of the star, the Lorentz force would become strong enough to deform its crust, thereby *twisting up* the external magnetic field. In such a situation, a persistent current will flow through the magnetosphere, supported by emission of light ions (e.g. H, He, C) and electrons from the neutron star surface. The decay of this current outside of the star is an efficient mechanism for converting magnetic energy to X-rays, and for inducing rapid variations in the X-ray flux.

To see how the persistent current will modify the structure of the magnetosphere, we find axisymmetric force-free equilibria outside a (non-rotating) spherical surface, $\nabla \times \mathbf{B} = \alpha(\mathcal{P})\mathbf{B}$. These equilibria form a one-dimensional sequence labeled by the flux parameter $\mathcal{P} = \mathcal{P}(R, \theta)$, with poloidal magnetic field $\mathbf{B}_P = \nabla\mathcal{P} \times \hat{\phi}/R\sin\theta$. As a major simplification we consider self-similar configurations

$$\mathcal{P} = \mathcal{P}_0(R/R_{\rm NS})^{-p}F(\theta), \qquad B(R,\theta) \sim F(\theta) \times (R/R_{\rm NS})^{-(2+p)}, \tag{1}$$

following Lynden-Bell & Boily (1994). The radial index p is uniquely determined by a single parameter C, which is related to the strength of the current:

$$p(p+1)F + \sin^2\theta \frac{\partial^2 F}{\partial(\cos\theta)^2} = -CF^{1+2/p}. \tag{2}$$

Choosing a dipole field at a zero current, $p(C)$ is determined by the *three* boundary conditions, $B_r(R, \theta = \pi/2) = 0$, $B_r(R_{\rm NS}, \theta = 0) = {\rm const}$, $B_\phi(R, \theta = 0) = 0$. The index p is most conviently expressed as a function of the net twist $\Delta\phi_{\rm N-S}$ between the north and south magnetic poles (Fig. 1a).

3. Resonant Scattering

The current-currying charges also provide a significant optical depth to resonant cyclotron scattering. For a particle of charge Ze and mass M, the resonant cross-section is $\sigma_{\rm res}(\omega) = (\pi^2 Ze^2/Mc)\,(1+\cos^2\theta_{kB})\delta(\omega-\omega_c)$. The optical depth is determined by relating the particle density n_Z to the twist in the magnetic field through $(Ze)n_Z v_Z = \epsilon_Z(c/4\pi)|\nabla\times\mathbf{B}|$. In our self-similar model,

$$\left(\frac{v_Z}{c}\right)\tau_{\rm res} = \frac{\pi\epsilon_Z}{8}\left(1+\cos^2\theta_{kB}\right)\left[\frac{F(\theta)}{F(\pi/2)}\right]^{1/p}\Delta\phi_{\rm N-S}. \tag{3}$$

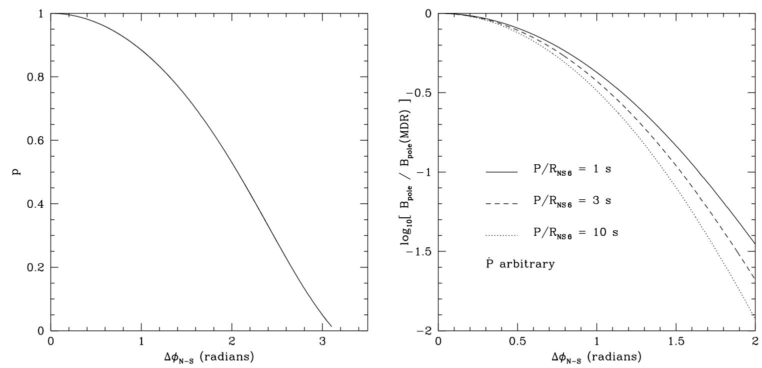

Figure 1. (a) The radial index p as a function of the twist $\Delta\phi_{\rm N-S}$. (b) The actual polar field inferred from spin parameters P and $\dot{P}$, compared with the magnetic dipole formula.

Thus the optical depth is $\tau_{\rm res} \sim (v_Z/c)^{-1}$ for strong twists $\Delta\phi_{\rm N-S} \sim 1$. Remarkably it is *independent of the mass and charge of the scatterers, the radius, or the resonant frequency.*

4. Implications for X-ray Spectra and Pulse Profiles

- *Surface Heating.* If ions and electrons supply the current, then the stellar surface is heated at the rate

$$L_X \simeq 3\times 10^{35}\,\epsilon_{\rm ion}\left(\frac{B_{\rm pole}}{10^{14}\ {\rm G}}\right)\left(\frac{B_\phi}{B_\theta}\right)_{\theta=\pi/2} \qquad {\rm erg\ s}^{-1}. \tag{4}$$

  (The electrons are electrostatically accelerated downward above the anode.) This is comparable to the observed luminosities of AXPs and SGRs. A global twist will decay on the timescale

$$t_{\rm decay} = \frac{E_B - E_B({\rm dipole})}{L_X} = 30\,\epsilon_{\rm ion}^{-1}\left(\frac{B_{\rm pole}}{10^{14}\ {\rm G}}\right)\Delta\phi_{\rm N-S} \qquad {\rm yr}. \tag{5}$$

- *Resonant Comptonization.* Both ions and electrons can be expected to move mildly relativistically where they resonantly scatter $1-10$ keV photons. The product of the mean frequency shift $\langle\Delta\omega/\omega\rangle$ per scattering with the expected number of scatterings is $O(1)$ when $\Delta\phi_{\rm N-S} \sim 1$ radian. Therefore, multiple scattering at the cyclotron resonance by the moving charge carriers will create a non-thermal spectral tail to the X-ray flux emerging from the surface. At optical depths $\lesssim 1$, the hardness of the spectrum increases with the number of scattering and thus with the resonant optical depth.

- *Pulse Profiles.* The emergent pulse profile is strongly modified by magnetospheric scattering. Three effects enter here: the optical depth $\tau_{\rm res}(\theta)$

is anisotropic, vanishing toward the magnetic poles; the resonant surface is aphserical; and the scattered radiation tends to be beamed along the magnetic field (in part because of the motion of the charge carriers). The pulse profile will be approximately frequency-independent in this self-similar model.

- *Ion Cyclotron Resonance.* The ion component of the current will generate a *comparable* optical depth to the electron component in a self-similar magnetosphere (at frequencies below the surface cyclotron frequency). Since the ion cyclotron resonance sits much closer to the star (at $\sim 10-20$ km for $2-10$ keV photons), it is more sensitive to the presence of higher magnetic multiples. Thus, a combination of ion and electron scattering in a multipolar magnetic field will produce an energy dependent total profile which is more complex at higher energies. An ion cyclotron emission line would be a clear observational signature of surface heating by magnetospheric charges.

- *SGR/AXP spindown.* When twisted, the magnetic field drops off more slowly than $\sim R^{-3}$. Thus the real polar field inferred from $P, \dot{P}$ is smaller than the magnetic dipole formula would imply, while the braking index becomes $n = 2p + 1 < 3$ (Fig. 1b). Our model predicts that the spindown rate increases with the optical depth to resonant scattering, and hence with the hardness of the persistent X-ray spectrum. In fact the active SGRs 1806-20 and 1900+14 both have higher $\dot{P}$ and harder X-ray spectra than any AXP. The quiescent SGR 0525-66 has a softer spectrum. We predict that its spindown rate, when measured, will be intermediate between these sources and the AXPs.

- *Giant Flare Mechanism* There are two generic possibilities for the production of the giant flares of the SGRs, in the framework of our model: (i) giant flares may result from a sudden change (unwinding) in the internal magnetic field, implanting a twist into the magnetosphere; or alternatively (ii) the twist may build up more gradually in the magnetosphere, leading to a sudden relaxation in close analogy with Solar flares. Measurements of hardening/softening of the persistent X-ray spectrum, changes in pulse profile, and changes in spindown rate provide a way of discriminating between these possibilities. In particular, the simplified pulse profile observed in SGR 1900+14 after the 27 August 1998 giant flare (Woods et al. 2000) can be explained by an increase in the currrent at the radius of the electron cyclotron resonance.

References

Duncan, R.C. and Thompson, C., 1992, ApJ, 392, L9

Lynden-Bell, D. and Boily, C., 1994, MNRAS, 267, 146

Thompson, C., Lyutikov M., Kulkarni S., `astro-ph/0110677`

Woods, P., et al. 2001, ApJ, 552, 748